

# **A Very High Bit Rate Broadband Acoustic Modem For Short-to-Medium Range Data Transmission in Ports and Shallow Water using Spread Spectrum Modulation and Decision Feedback Equalizing**

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## **LONG-TERM GOALS**

The long term goal of this program is to develop underwater acoustic modem technology for real-time wireless transfer of high-definition images and sonar data over short-to-medium range operations in shallow water. A specific deployment goal is an acoustic tether that provides human-in-the-loop capability for an AUV performing a ship hull inspection.

## **OBJECTIVES**

The objective of this project is to develop a prototype Very High Bit Rate Broadband Acoustic Modem, capable of achieving true data rates of up to 100 kbps at a maximum range of 300 meters, for a maximum rate-range of 30 kbps-km. The frequency band of operation is 262 kHz to 375 kHz approximately. High data rates are made possible using the high-resolution decision feedback equalizer with parallel algorithm for tracking and compensating large Doppler developed by Dr. Beaujean.

This prototype modem consists of two components: a topside acoustic modem and an underwater acoustic modem. The notebook personal computer is to run the receive modem software as well as a limited user interface. The receive modem software demodulates, decodes and reconstructs the data in real-time, and send it to the user interface and display software. The communications link between the portable topside unit and the notebook computer is TCP/IP over Ethernet. The benefit of physically separating the portable topside unit from the computer hosting the receive modem software is that the computer could be deployed remotely from the portable topside unit. The Ethernet communications link between the computer and portable topside unit allows many physical connectivity options, wired or wireless. The underwater acoustic modem is a small, low power, self-contained unit suitable for mounting on a hovering Autonomous or Unmanned Underwater Vehicle. It encodes and modulates

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input data from devices such as cameras, sonars and sensors, and uplinks the data to the topside acoustic modem in very high bit rate, broadband one-way acoustic transmissions.

## APPROACH

### *Brief Review of the Transmission Modes*

The transmitted message contains three separate signals: a broadband chirp is used as the message trigger, followed by a preamble, which provides basic information about the message, and the data frame. The data frame is a combination of a short synchronization and training sequence followed, after a short dead time, by a data packet. The message trigger is the sum of a tone of frequency of 375 kHz and a linear frequency-modulated chirp with a carrier frequency of 360 kHz (347-373 kHz), using 26 kHz of bandwidth. The preamble contains the type of modulation and symbol duration used in the data frame. The signal can be transmitted using symbols of duration 40  $\mu$ s, 20  $\mu$ s or 13.3  $\mu$ s. The modulation is either BPSK or QPSK. In effect, the preamble uses direct-sequence spread spectrum (DSSS) to reduce the negative impact of fading. The 3 bits used to code this information are spread using a Gold code over 256 bits. The resulting Gray-coded PN-sequence is QPSK-modulated at a carrier frequency of 300 kHz, using 50 kHz of bandwidth. Each symbol is shaped using a raised-cosine time window. The transmitted preamble also contains a tone of frequency of 375 kHz. The data frame is modulated using either Binary Phase Shift Keying (BPSK) or Gray-coded Quaternary Phase Shift Keying (QPSK). Table I summarizes the salient characteristics of a modem message. At the fastest data rate (mode 5), HERMES can transmit an uncompressed DIDSON frame (400000 bits) in 4.6 seconds. A more bandwidth efficient version of mode 5 is under work, capable of transmitting the same information in 4.2 seconds. Note that the bit efficiency is computed based on the full output acoustic power (32W) of the high-speed uplink source.

**Table I - Data Packet Specifications**

<b>Mode</b>	<b>0</b>	<b>1</b>	<b>2</b>	<b>3</b>	<b>4</b>	<b>5</b>
Modulation Type	BPSK	BPSK	BPSK	QPSK	QPSK	QPSK
Symbol Duration	40 $\mu$ s	20 $\mu$ s	13 $\mu$ s	40 $\mu$ s	20 $\mu$ s	13 $\mu$ s
Symbol Bandwidth	25 kHz	50 kHz	75 kHz	25 kHz	50 kHz	75 kHz
Information bits/ frame	9120	9120	9120	9120	9120	9120
Packet duration (ms)	0.5491	0.2745	0.1830	0.2745	0.1373	0.0915
Message duration (s)	0.5615	0.2869	0.1954	0.2869	0.1497	0.1039
Information rate (bps)	16243	31784	46668	31784	60935	87768
Packet coded rate (bps)	25000	50000	75000	50000	100000	150000
Bits-per-Joule (bit/J)	507.6	993.3	1458.4	993.3	1904.2	2742.8
(at 32W of acoustic power, up to 180 m range)						

The data are collected using the high-resolution, low-noise acquisition system developed by EdgeTech in collaboration with FAU. The acquisition system produces complex base-band signals with a 24-bit resolution. This data is processed with a commercial off-the-shelf notebook PC, connected to the acquisition unit via Ethernet, using the Very High Bitrate Acoustic Modem decoder. Each incoming message is detected, authenticated, equalized and decoded, and the output is relayed to a de-multiplexer which routes relevant information to each application. At present, the applications are the DIDSON topside display and vehicle control display.

The core of the decoder is a set of parallel Doppler-compensated lattice-ladder decision feedback equalizers combined with soft-decision BCH decoding. Each equalizer within the set is started at a different location of the training sequence, with a number of feed-forward taps sufficient to cover most of the multipath and a small number of feedback taps. By doing so, each equalizer identifies a path in the least-square sense and creates a time-varying filter that best matches this portion of the multipath. Only the equalizers producing the lowest mean-squared error estimation of the training sequence are retained. This technique requires a very good time resolution of the acoustic channel, which can be obtained with the broadband acoustic signals transmitted by the Very High Bitrate Acoustic Modem source. Each equalizer binary output is combined with the corresponding binary output from the other equalizers and is decoded with a soft-decision BCH routine. The integrity of the received message is tested using a CRC-32, and the information is relayed to the de-multiplexer, along with a quality level for each bit and an error flag.

## **WORK COMPLETED**

All the tasks pertaining to the base effort of the STTR Phase II project have been completed:

- Task 1: System Specifications
- Task 2: Portable Topside Unit (Refer to Figure1)
- Task 3: Transducer Development (Refer to Figure1)
- Task 4: Topside Receiver Modem Software
- Task 5: Underwater Transmit Modem Software (Refer to Table 1)
- Task 6: Underwater Modem Electronics Stack (Refer to Figure 1)
- Task 7: Data Acquisition Server/Client Software
- Task 8: User Interface and Display Software
- Task 9: Underwater Modem Pressure Vessel
- Task 10: Underwater Device Interface Software
- Task 11: Data Compression Formats
- Task 12: Topside Modem Integration and Test
- Task 13: Underwater Modem Integration and Test
- Task 14: System Integration and Test
- Task 15: System Demonstration and Verification (Refer to Figures 2, 3 and Table III)

The following Option-A tasks have been completed:

- Task A-1: System Specifications
- Task A-2: Low Bit Rate Topside Downlink Module
- Task A-3: Topside Downlink Module Integration
- Task A-4: Topside User Command Interface Software
- Task A-5: Underwater Transducer
- Task A-6: Underwater Low Bit-Rate Receiver
- Task A-7: Underwater Modem Pressure Vessel Modifications
- Task A-8: Underwater Low Bit Rate Receive Modem Software

Task A-9 (System Integration and Test) is approximately 80% complete. The completion of task A-10 (System Demonstration and Verification) will follow that of task A-9.



**Figure 1. Completed Underwater Modem Electronics Stack (left), Jetasonic H320 Source Transducer (center) and Portable Topside Unit (right) for the Very High Bit Rate Acoustic Modem.**

## RESULTS

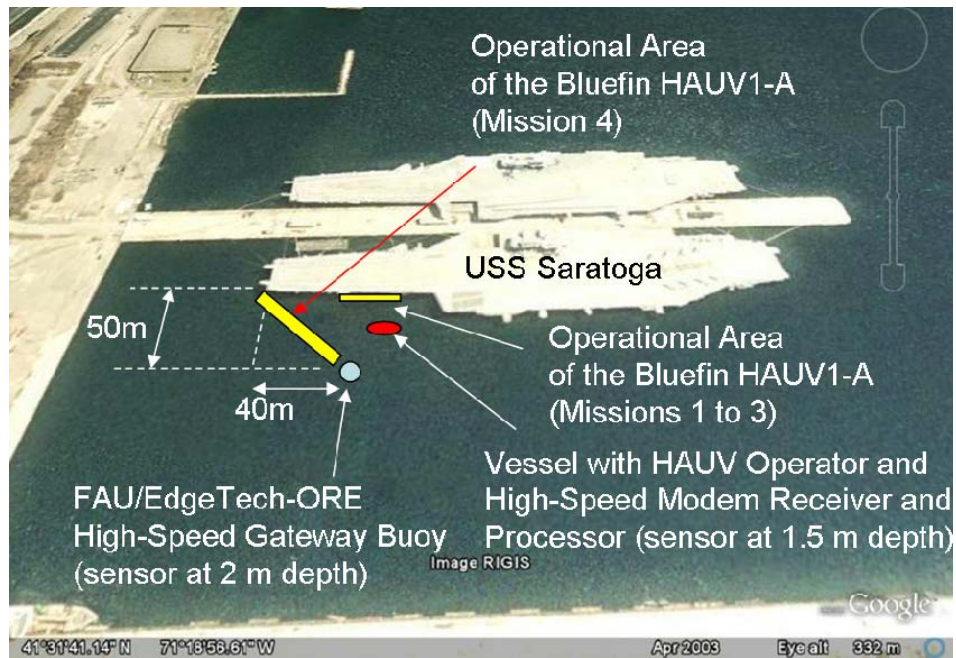
### *Experimental Summary*

The integration and test of the topside modem, underwater modem and high-speed acoustic uplink system has been threefold: (1) Laboratory test using direct transducer coupling; (2) System calibration in the acoustic tank at FAU SeaTech; (3) Field tests in the FAU SeaTech marina. During the later field tests, the source was operating at 32 W of output acoustic power (full power). The maximum operating range of the system was 120 m. In 2 to 3 m of water, at 95 m range and using the fastest transmission mode (87,768 data bits-per-second, 2,742.8 bits-per-Joule and 8,337 bps-km), 100% of the messages were detected, of these 97.561% were decoded with an average bit-error-rate of 0.12116%. Background noise measurements clearly indicated that the range could be further increased by reducing the impact of burst noise.

An analog band-pass filter was designed and assembled to that purpose. The high-speed acoustic modem receiver was equipped with this analog filter during the final system demonstration and verification on July 25<sup>th</sup>, 2008. The final system demonstration and verification has been two-fold: first at AUV Fest 2008 in Newport, RI (May 14<sup>th</sup>, 2008, Figure 2) and at the FAU SeaTech marina on July 25<sup>th</sup>, 2008 (Figure 3).

During the SeaTech demonstration, the source was operating at 32 W of output acoustic power (full power). The relative speed between the source and the receiver did not exceed 1 m/s. The maximum operating range of the system was 180 m. In 2 to 3 m of water, at 120 m range and using the fastest transmission mode (87,768 data bits-per-second, 2,742.8 bits-per-Joule and 10,532 bps-km), 91.25% of the messages were detected, of these 87.612% were decoded with an average bit-error-rate of 0.36989%. The SNR fluctuated between 17 dB and 20 dB.

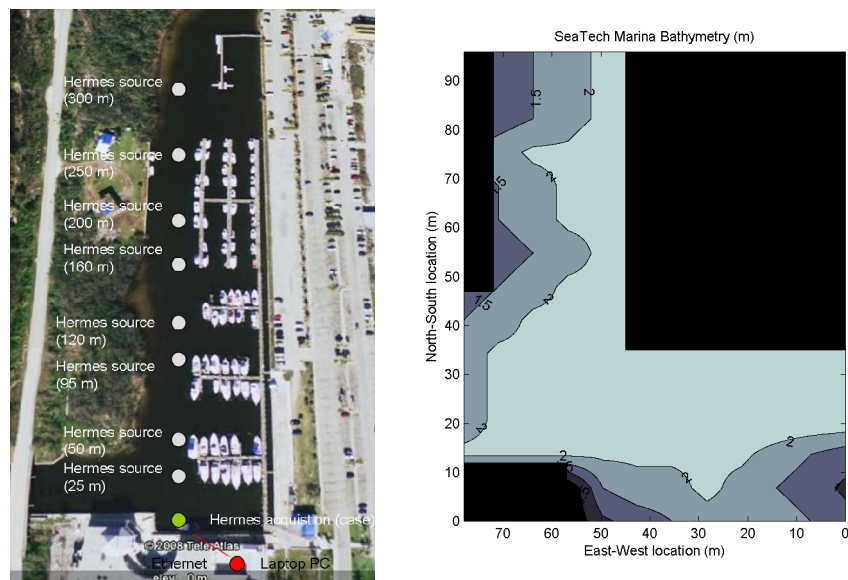
During the same test, at 160 m range and using the fastest transmission mode (87,768 data bits-per-second, 2,742.8 bits-per-Joule and 14,043 bps-km), 70% of the messages were detected, of these 75% were decoded with an average bit-error-rate of 0.36811%. The SNR was approximately 14 dB.



**Figure 2. AUV Fest 2008, Saratoga hull search experiment (NUWC-Newport, 05/14/08)**

### **System Demonstration and Verification**

This section provides a more detailed description of some of the results obtained on July 25<sup>th</sup>, 2008. The source transducer was placed at 0.5 m below the surface and was placed at a distance of 25, 50, 95, 120, 140, 160 and 180 m (Figure 3). Figure 3 also shows the bathymetry in the SeaTech marina (at high-tide). The sea bottom was composed of mud and fine sand. The relative speed between the source and the receiver did not exceed 1 m/s.



**Figure 3. Aerial view of the location for experiments in SeaTech Marina, Port Everglades, Florida, indicating source and receiver positions (left), and bathymetry data (right)**

The received signal PSD and SNR were measured at 1 m, 25 m, 50 m, 95 m, 120 m, 160 m, 200 m, 250 m and 300 m. Table II shows the measured SNR at each range in the data communication band and indicates that the SNR becomes marginally low beyond 200 m.

**Table II – Communication band SNR vs. Range**

Range	1 m	25 m	50 m	95 m	160 m	200 m
Measured SNR, 280 kHz to 320 kHz (dB)	64	36	30	20	14	9

Table III shows the performance analysis of the high-speed acoustic uplink for mode 4. Each symbol is BPSK-modulated and used 75 kHz of bandwidth. Table IV shows the performance analysis of the high-speed acoustic uplink for mode 5. In this case each symbol is QPSK-modulated and used 75 kHz of bandwidth. Figure 4 shows the percentage of messages that have been properly detected, authenticated with a percentage of corrupted data bits lower than 10%, for modes 4 and 5. This percentage is shown as a function of range. Figure 5 shows the BER averaged across all the messages that have been properly detected, authenticated with a percentage of corrupted data bits lower than 10%, for modes 4 and 5. This percentage is shown also as a function of range. Figure 6 shows the percentage of data bits actually received correctly, including only the messages that have been properly detected, authenticated with 10% or less of corrupted data bits.

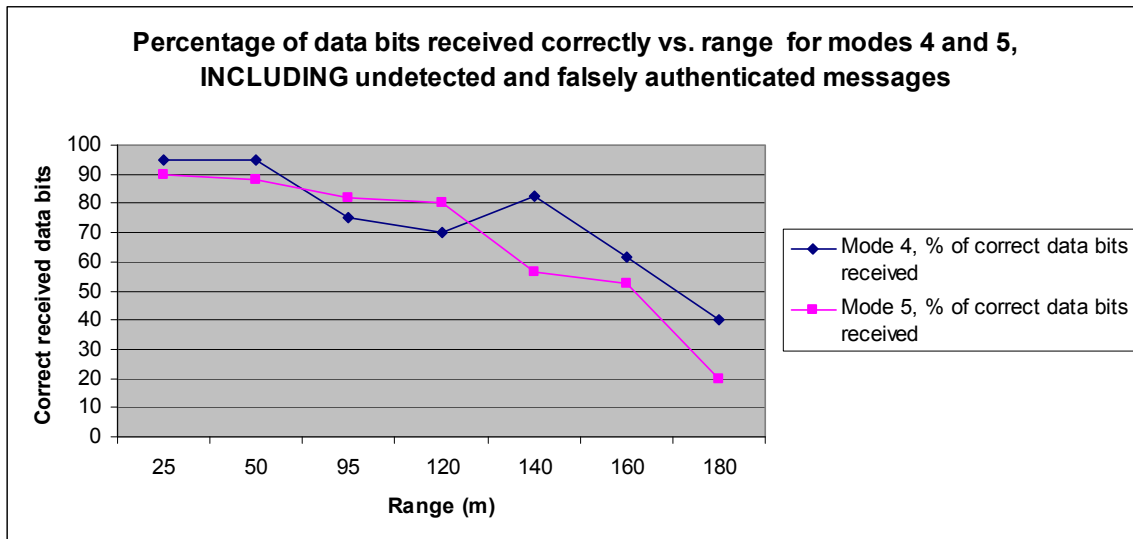
The results clearly indicate that the high-speed acoustic uplink can operate reliably in a difficult environment at ranges exceeding 160 m. At 32 W of acoustic power, the system can be operated up to 180 m in very shallow waters. The maximum range can be further increased using a more powerful source if necessary.

**Table III - Summary of Results for 07-25-08 – Mode 4**

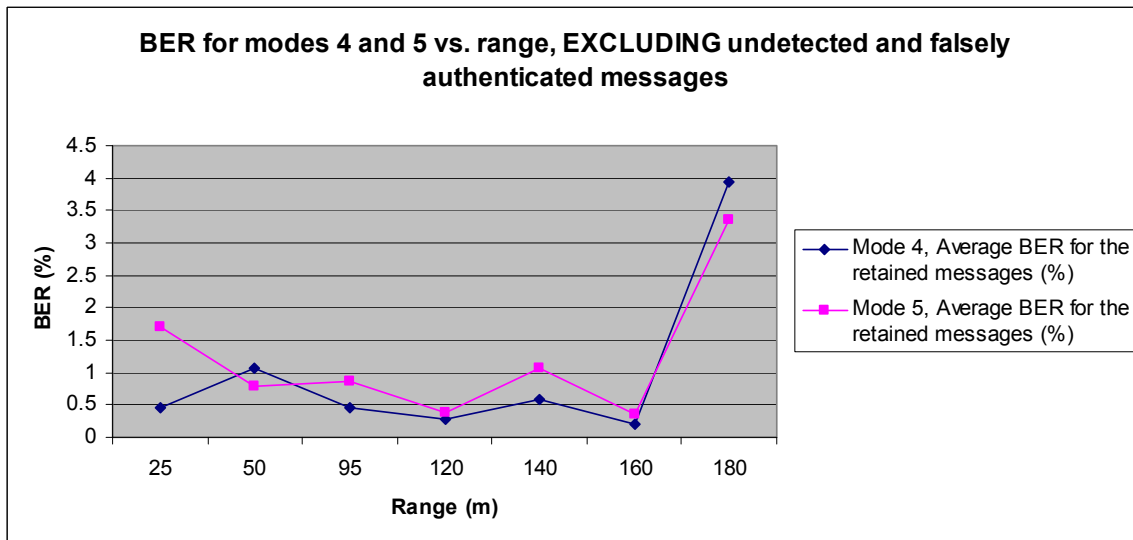
Range	25	50	95	120	140	160	180
No of messages transmitted	40	60	60	80	80	60	40
No of messages detected and authenticated	45	66	54	76	91	62	47
No of false positives	5	6	0	0	11	2	7
Mode 4, % of detected & authenticated messages with BER < 10% (filters out false positives, out-of-sync & erroneous identification)	84.4444	86.3636	83.3333	73.6842	72.5275	59.6774	34.0426
Mode 4, Average BER for the retained messages (%)	0.45937	1.0713	0.44981	0.27334	0.57516	0.21041	3.9508
No of data bits transmitted	364800	547200	547200	729600	729600	547200	364800
No of correct data bits received (retained messages, BER < 10%)	346559	519839	410399	510719	601920	337439	145920
Mode 4, % of correct data bits received (retained messages of BER < 10%)	94.9997	94.9998	74.9998	69.9999	82.5	61.6665	40

**Table IV - Summary of Results for 07-25-08 – Mode 5**

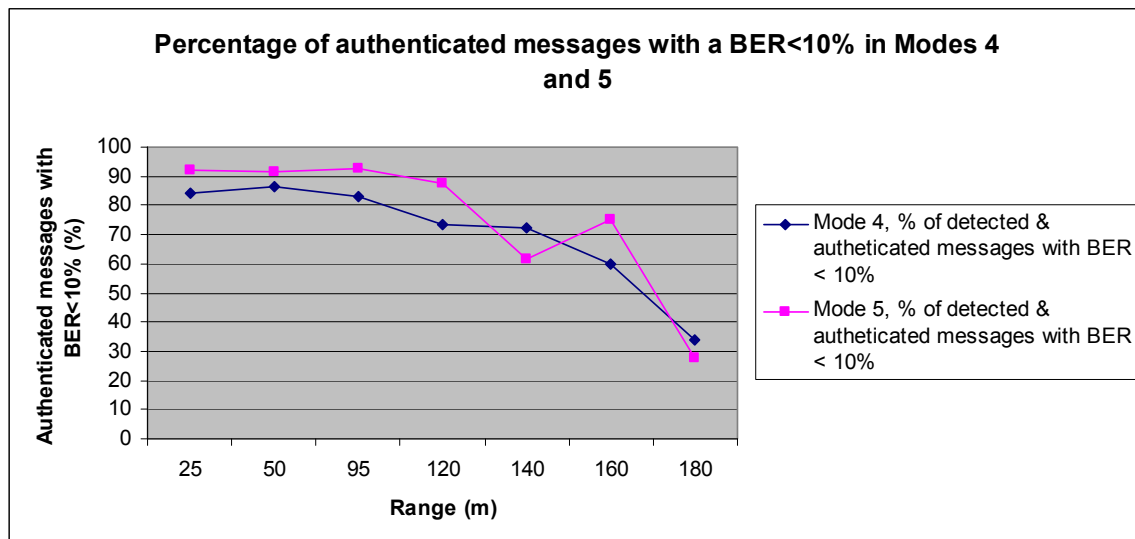
Range	25	50	95	120	140	160	180
No of messages transmitted	40	60	60	80	80	40	40
No of messages detected and authenticated	39	58	53	73	73	28	29
No of false positives	0	0	0	0	0	0	0
Mode 5, % of detected & authenticated messages with BER < 10% (filters out false positives, out-of-sync & erroneous identification)	92.3077	91.3793	92.4528	87.6712	61.6438	75	27.5862
Mode 5, Average BER for the retained messages (%)	1.7124	0.78906	0.86779	0.36989	1.0768	0.36811	3.3594
No of data bits transmitted	364800	547200	547200	729600	729600	364800	364800
No of correct data bits received (retained messages, BER < 10%)	328320	483359	446879	583679	410399	191520	72959
Mode 5, % of correct data bits received (retained messages of BER < 10%)	90	88.3332	81.6665	79.9999	56.2499	52.5	19.9997



**Figure 4. Percentage of data bits received correctly vs. range for modes 4 (75 kHz, BPSK) and 5 (75 kHz, QPSK), INCLUDING undetected and falsely authenticated messages. SeaTech marina, 07/25/08.**



**Figure 5. BER for modes 4 (75 kHz, BPSK) and 5 (75 kHz, QPSK) vs. range, EXCLUDING undetected and falsely authenticated messages. SeaTech marina, 07/25/08.**



**Figure 6. Percentage of authenticated messages with a BER<10% in modes 4 (75 kHz, BPSK) and 5 (75 kHz, QPSK). SeaTech marina, 07/25/08.**

## IMPACT/APPLICATIONS

Having human-in-the-loop capability is essential during hull surveillance and port security missions, and requires the transmission of images to a remote user. At the present time, cables are used, which prevents the usage of hovering AUVs in operating in confined areas, near propellers and around pilings. An alternate solution is to combine the latest technology of data compression with a broadband acoustic modem operating at short range. The proposed work will demonstrate, during realistic missions, that a high-speed acoustic modem can be deployed to transfer high-quality sonar images in real-time and provide human-in-the-loop capability to a hovering AUV.

## RELATED PROJECTS

“High-Speed, High-Frequency Multi-Point Acoustic Modem (HS-HF-MPAM) with Low-Frequency Acoustic Control Loop for Real-Time Transmission of Compressed AUV-Carried High-Resolution Images and Navigation Data in Ports and Very Shallow Waters”. Principal Investigator: Dr. Pierre-Philippe Beaujean, Associate Professor. Sponsored by the Office of Naval Research (Dr. Thomas Swain). ONR award no. N00014-05-1-0604. FAU grant no. 1615-117-42. \$286,839 in competitive bidding. (Planned period of performance 10/15/07 to 05/30/09).

“Installation and Experimentation of a High-Speed, High-Frequency Acoustic Modem (HS-HFAM) coupled with a Wavelet-Based Embedded Compression Unit on the CETUS II for Real-Time Transmission of Compressed DIDSON Data to a Topside Unit”, Dr. P-P. Beaujean (PI), Sponsored by the Office of Naval Research (Dr. Swain). ONR award number N00014-05-1-0604.

“High-Speed, High-Frequency Acoustic Modem (HS-HFAM) Unit for Real-Time Transmission of Multi-User Multiplexed Data and Diver-Carried DHINS Image and Navigation Data to a Topside Unit for Operations in Ports and Very Shallow Waters”, Dr. P-P. Beaujean (PI), Sponsored by the Office of Naval Research (Dr. Swann). ONR award number N00014-05-1-0604.

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